

Design and Evaluation of a Reinforced Advanced-Grid Stiffened Composite Structure

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A composite grid-stiffened structure concept was selected for the payload fairing of the Minotaur launch vehicle. Compared to previous designs, this concept is lighter weight and requires reduced manufacturing costs. Various failure mechanisms were examined for the composite grid-stiffened structure. The controlling criterion for this design was determined to be joint peel-off failure. The identification of this failure mechanism and the assessment of bounding strains to control it, required extensive test and analysis effort. The final fairing design incorporated an undesirably thick skin to reduce the strain between the skin and ribs. This project investigated a means of controlling joint failure of the un-reinforced grid-stiffened structure in an effort to reduce the skin thickness. Implementing lightweight foam inserts between the stiffeners on the interior of the fairing delayed failure to higher loads. A foam reinforced test panel, designed with equal mass to the current structure, withstood a substantially greater compressive force. The alternative concept also demonstrated an improved response, failing in global buckling instead of experiencing early failure due to joint strain.

I. Introduction

The Air Force Research Laboratory (AFRL) continues to develop new spacecraft and launch vehicle structures that will enhance the performance and cost effectiveness of future Air Force missions. In recent years a new payload fairing was developed for the Minotaur launch vehicle. The carbon fiber composite fairing consists of a laminate skin co-cured to a reinforcing Advanced Grid-Stiffened (AGS) rib structure, as shown in Figure 1. Compared to previous sandwich panel designs, this concept is lighter weight (per volume) and allows reduced manufacturing costs. In 2002 the new Minotaur fairing was manufactured by Boeing and delivered to the Air Force Research Laboratory for flight qualification tests. The statically applied load cases exceeded the worst case dynamic flight conditions by a 25% margin. The fairing maintained structural integrity under the peak load while remaining within the required displacement envelope for payload safety.

At the outset of the Minotaur fairing development, global buckling instability was assumed to be the controlling factor in the design process; however, substructure test panels demonstrated early failure. Extensive efforts were made by Boeing to identify the failure mode. Ultimately joint peel-off strain, characterized by the first strain invariant (J1), was determined to be the controlling criterion. Joint peel-off is caused by relative rotation of the skin and ribs structures. To minimize the weight of the fairing, the skin pockets are allowed to displace causing localized non-linear buckling behavior. As a result of the skin buckling patterns, a bending moment forms in the skin that tends to peel it from the AGS, inducing local failure. Once failure initiates locally, the crack quickly propagates along the entire joint between the skin and stiffener structure, leading to global failure of the fairing. To prevent joint peel-off, an undesirably thick skin detail was incorporated on the launch vehicle. Understanding the failure mechanism of the Minotaur fairing enhances the possibility of improving the efficiency of the structure. The objective of this study was to investigate a means of stabilizing the skin/rib interface without increasing the system mass of the fairing. A successful concept will demonstrate greater strength than the current Minotaur fairing configuration.

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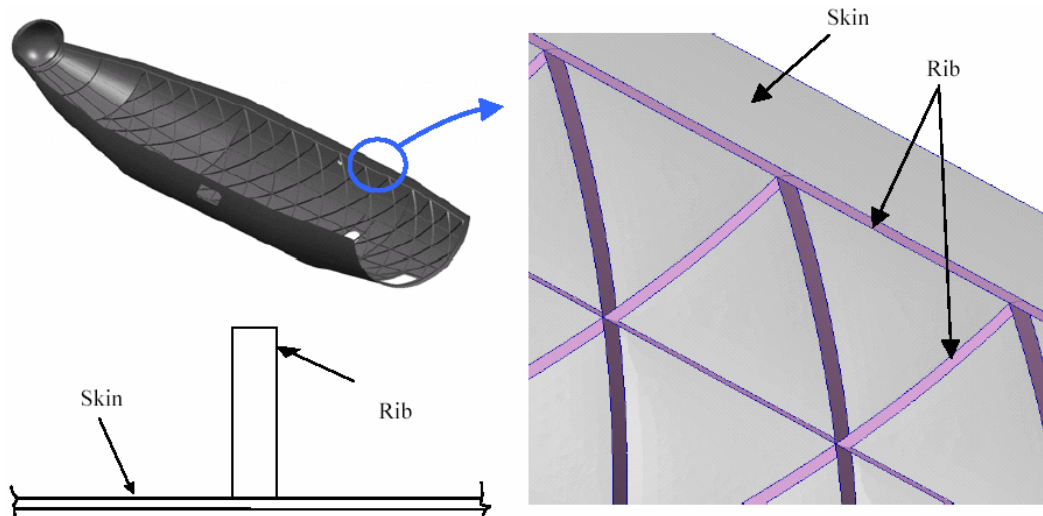


Figure 1. Minotaur Fairing Composite Grid-Stiffened Structure

AFRL is highly confident in the current composite grid-stiffened configuration for one-time-use applications such as expendable launch vehicle payload adapters and fairings. The extension of this technology into aircraft applications or similar lightweight, long-life structures is hampered by the need to ensure the integrity of the joint under fatigue cycling, dynamic or impact events, etc. AFRL and CSA Engineering, Inc. have investigated several alternative means to stabilize the skin/rib joint. Reinforcing the interface in a manner that significantly improves the pre-crack performance is difficult; however, joint stabilization will ultimately lead to greater performance and versatility of the advanced grid-stiffened architecture.

II. Experimental Data with Analytical Comparisons

Four alternative design concepts that inherently prevented rotation at the skin/rib interface were developed and tested. The alternative concepts were designed on an equal mass basis with a baseline representation of the current Minotaur fairing. The alternative designs were: 1) Rohacell Reinforced, 2) Carbon Foam Reinforced, 3) Skinless, and 4) Double-Sided.

The nominal skin thickness of the Minotaur fairing is 12 plies; the first concept incorporated a thinner eight ply skin. The reduction in skin mass allowed for the implementation of a closed cell foam, Rohacell 71 IG, into the areas between the grid stiffeners on the interior side of the panel. The foam inserts were intended to dampen skin/rib rotation. The low density of the Rohacell foam is advantageous because a substantial amount of material can be integrated to support the rib at a relatively small weight penalty.

The second alternative reduced the skin thickness to six plies so Carbon Foam (CFoam) could be introduced to reinforce the AGS. CFoam is substantially denser than Rohacell; thus in order to maintain the panel's weight constraint, regions of the foam inserts not adjacent to the reinforcing structure were partially removed. The CFoam panel acted as the exterior surface of the design, dubbing as the vehicle's Thermal Protection System (TPS), because the material demonstrated the ability to resist extreme temperature loads. Integrating the TPS into the structure increased the structural system's mass allowance, which was the CFoam Reinforced concept's primary design advantage.

Alternative three was a departure from the CFoam Reinforced design that did not contain a carbon fiber composite skin. Instead the AGS was supported solely by a carbon foam panel. Similar to the CFoam Reinforced design, the Skinless concept used the flat foam surface as the exterior of the shroud, which doubled as the TPS. By completely removing the composite skin system, less CFoam needed to be removed from the interior foam surface to comply with the mass constraint. The practicality of this concept as well as the preceding concept depended on the compressive and flexural properties of the carbon foam, thus warranting material characterization tests.

The last alternative was named the Double-Sided concept because it was constructed by curing a thin skin to each side of the rib structure. The design intent was to reduce the rib rotation by supporting both edges of the helical and axial ribs thus eliminating the detrimental free edge of the AGS structure. The minimal skin thickness on each side of the grid promoted skin buckling. To prevent skin buckling in this design, pad-up plies were incorporated at

the middle surface of the skin and aligned unidirectionally with the rib. The additional thickness stiffened the skin near its interface with the AGS grid and prevented relative rotation at the joint.

The four alternative designs and the baseline departure of the current launch vehicle were evaluated through a three phase experimental plan that culminated in compressing integrated test panels until failure. Finite element models were then constructed to further analyze the behavior of the material in the experimental articles during the test.

The purpose of phase one was to evaluate the compressive strength of two foams: closed cell Rohacell with a density of 75 kg/m^3 and carbon foam with a 275 kg/m^3 density. The Rohacell foam displayed an average ultimate compressive strength of 1546 kPa. The maximum load was typically realized at a strain of 0.09 mm/mm and could be maintained by the material until a strain of 0.70 mm/mm. The carbon foam had an average maximum compressive strength of 4575 kPa, which occurred at a strain of 0.13 mm/mm. Figure 2, below, displays the compressive strength results for the two foams. The specific weight of the carbon foam was 3.7 times heavier than that of the Rohacell foam, but the average compressive strength was less than three times greater, meaning the Rohacell foam had a more impressive strength to weight ratio. The CFoam concepts were not discarded from the evaluation process due to the material's lower strength/weight ratio because the alternatives that included CFoam had an added advantage of incorporating the weight of the TPS into the structural system which reduced the weight penalty of the material.

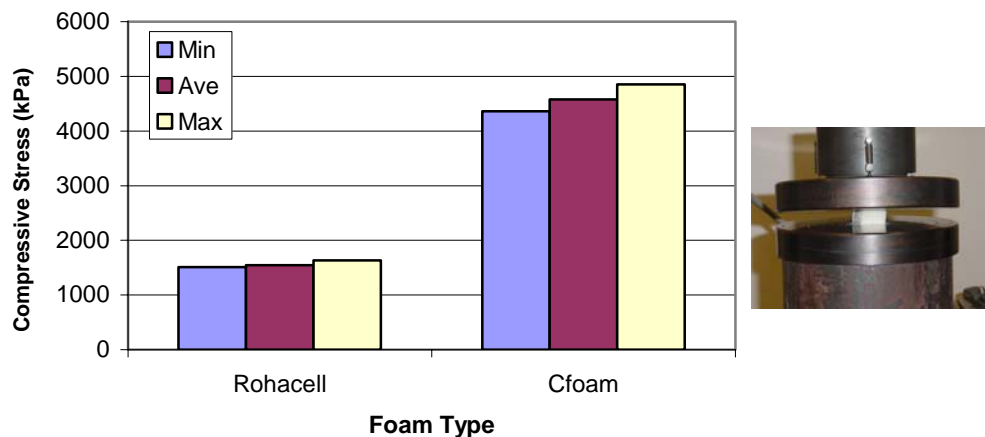


Figure 2. Compressive Strength Results for Rohacell and CFoam

Since the carbon foam comprised the outer surface of the launch vehicle in the second and third alternatives, bending tests were conducted to evaluate the flexural strength of the foam and assure it could withstand launch effects. The material was subjected to 3 and 4-point bending. The failure load from the experiment was used to determine the maximum bending stress in the specimen. Four to six specimens were tested in each of the bending tests. The earliest 3-point bending failure occurred under a stress of 85.5 kPa. The minimum bending strength experienced by a 4-point specimen was 80 kPa. In each case the material was found to fail at a stress greater than 69 kPa (10 psi), the worst perceived launch load, which validated the continued analysis of the CFoam reinforced concepts.

T-specimen coupons were produced to examine the pull-off strength between the skin and AGS grid for each skin configuration in the second phase of the test plan. An initial set of T-tests obtained the pull-off strength for each of the four skin configurations; however, issues with the specimen manufacturing procedure and the test setup produced faulty results. The general trend noted from the first round of pull-off tests was that coupons with thicker skins failed at higher loads. The results of experiments conducted after the first round of pull-off tests warranted accurate T-test results for the 8-ply configuration and the Baseline 12-ply skin configuration. The problems encountered in the initial tests were remedied and reliable data was achieved. Figure 3 displays the results of the second set of T-tests. This information was ultimately applied to a finite element model of the test to determine the allowable first strain invariant, which was a measure of the critical failure mechanism.

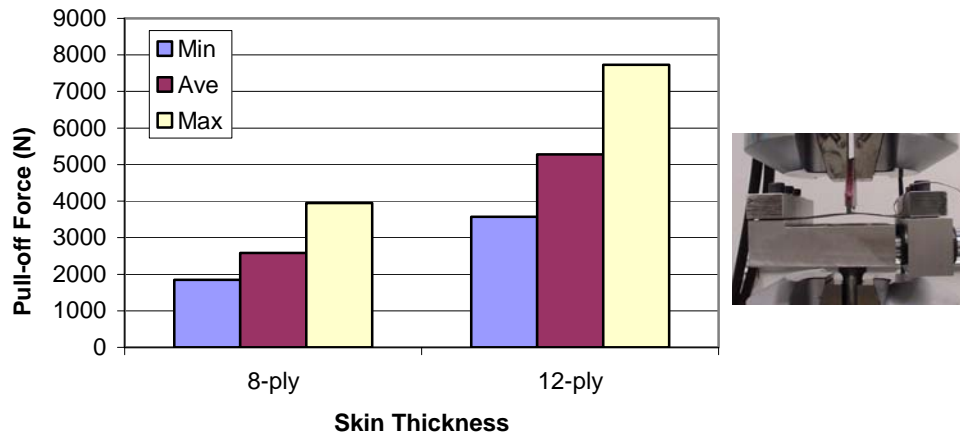


Figure 3. Pull-off Load Results for the 8 and 12-ply Skin Configurations

The final experimental stage was to manufacture integrated test panels and load them to failure. The panels were subjected to an increasing compressive force until the structure’s load carrying capability diminished. The failure loads of each alternative design were compared to that of the baseline panel to evaluate the effectiveness of the new concepts. In addition to the panel’s load response, opposing strain gages were mounted in the middle of the center axial rib to analyze the stiffener’s buckling behavior. A divergence in the strain gage responses indicates the rib is rotating in such a manner that it is no longer perpendicular to the skin. Table 1 displays the results from the panel tests. The only alternative to outperform the Baseline was the Rohacell Reinforced concept; it did so by 35 percent.

Table 1. Test Panel Failure Results

Concept	Failure Load (kN)	Comparison to Baseline	Rib Buckling (Y/N)
Baseline	97	NA	Yes
Rohacell Reinforced	131	35%	No
CFoam Reinforced	85	-12%	No
Skinless	58	-40%	No
Double-Sided	72	-26%	Yes

Each of the new concepts prevented rib buckling except the Double-Sided panel. The fourth panel was difficult to produce since it placed a skin on both sides of the AGS and a viable manufacturing process for such a structure does not currently exist. As a result, the test article did not accurately represent the intended design. The fact that the rib buckled is assumed to be an artifact of the fabrication difficulties, not a design flaw.

The load versus strain relationship for the Baseline panel during the compression test is displayed in Figure 4. After the panel was subjected to approximately 30 kN, the opposing strain gage’s output began to separate, indicating rib rotation. The opposing strain data from the Rohacell Reinforced panel’s center rib remained similar over the course of the entire test suggesting the reinforcing foam sufficiently stabilized the AGS structure, as shown in Figure 5.

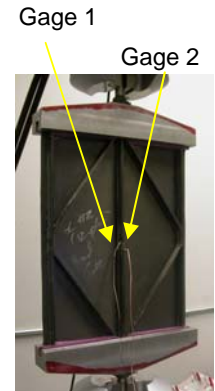
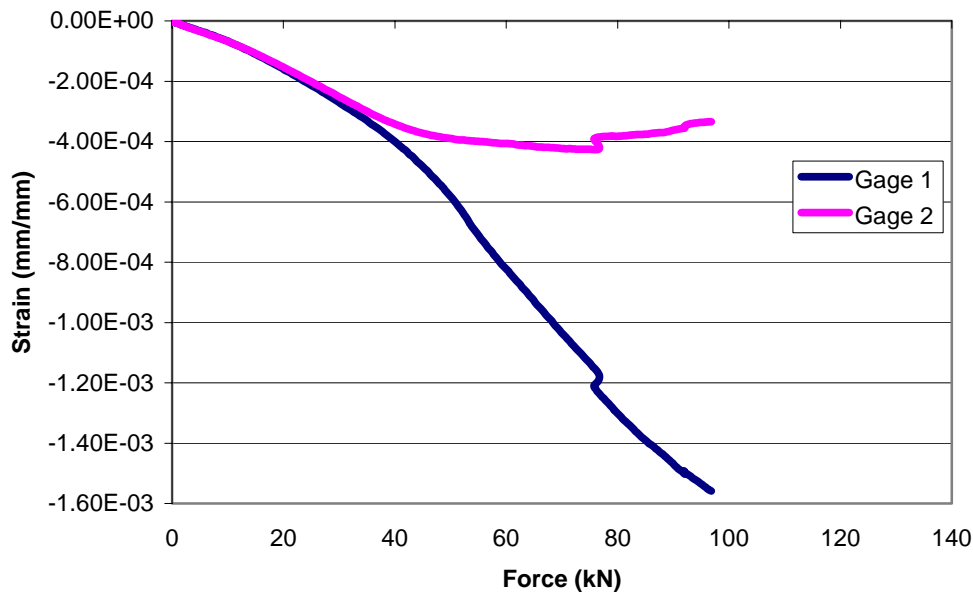


Figure 4. Baseline Panel's Load versus Strain Response

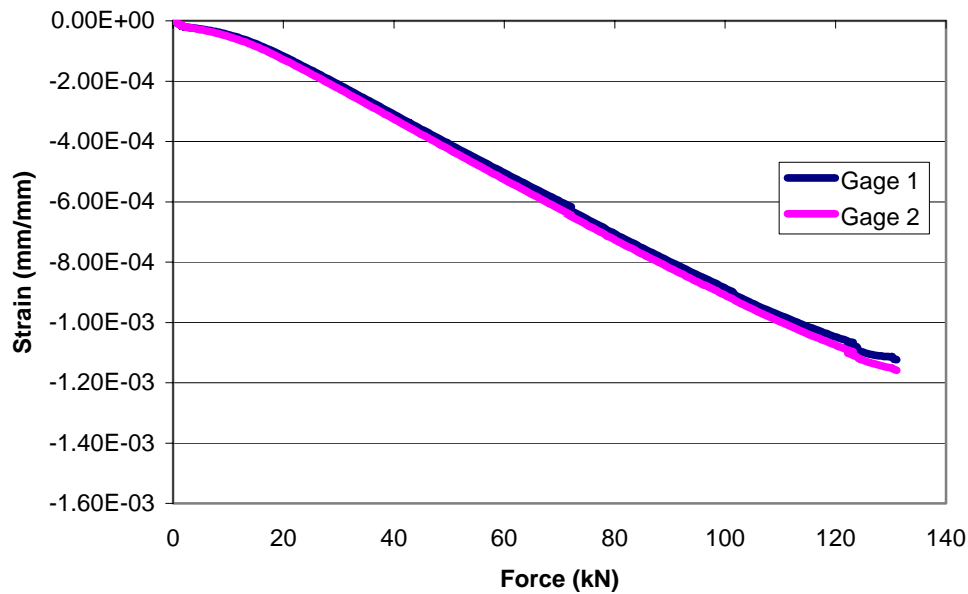


Figure 5. Rohacell Reinforced Panel's Load versus Strain Response

Finite element simulations were needed to further analyze the results of the empirical tests. Only the Rohacell Reinforced panel withstood a greater load than the nominal test article, so it was further analyzed with the Finite Element Analysis procedure. The Baseline panel was also examined so comparative conclusions could be drawn between it and the alternative concept. The average failure load from the T-specimen pull-off tests was applied to a two-dimensional Finite Element Model (FEM) of the experiment to determine the maximum first strain invariant in the fillet between the skin and ribs during the T-test. Seventy percent of the maximum J1 at T-specimen failure was used as the failure criterion during panel analysis. The results of the pull-off test simulations are shown below in Figure 6.

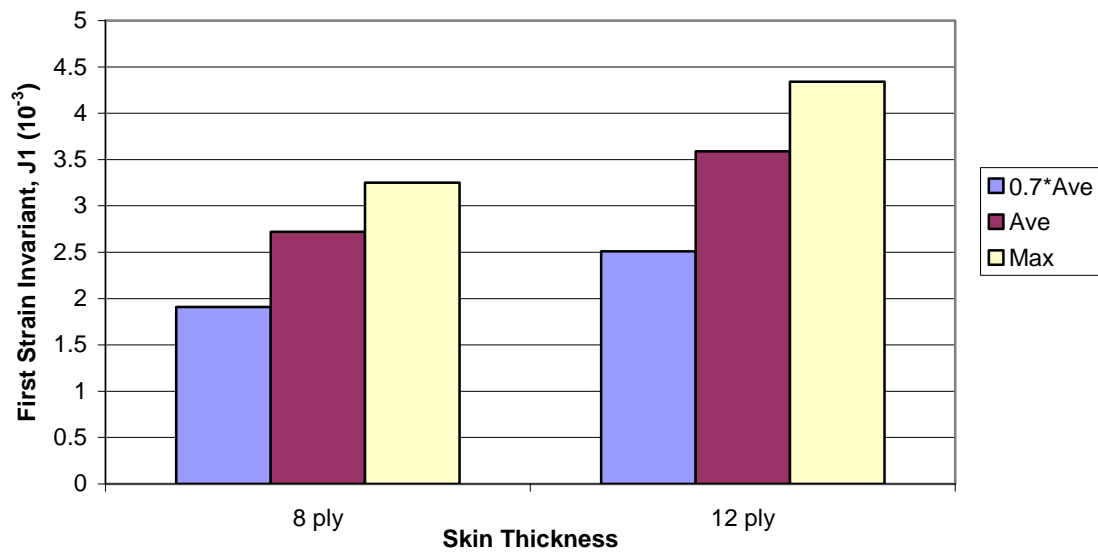


Figure 6. First Strain Invariant Values from T-specimen Simulations

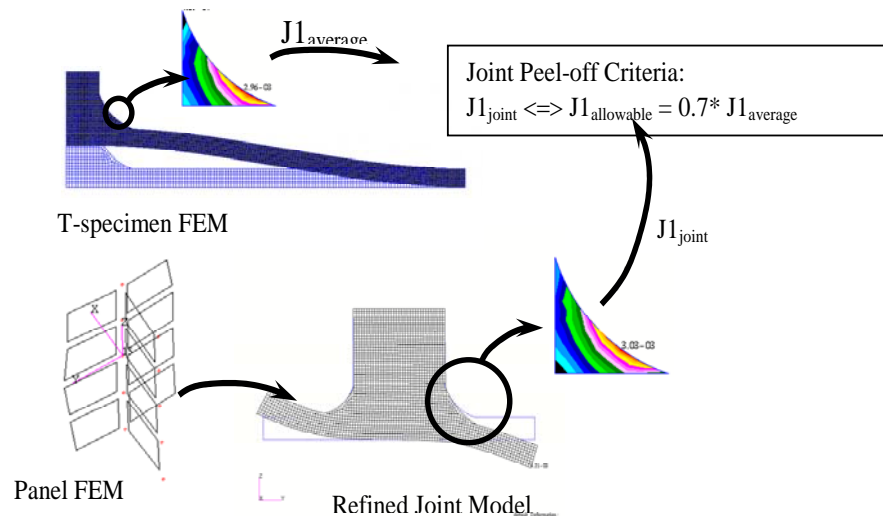


Figure 7. Joint Failure Criterion Development Process

Shell element models of the test panels were then constructed to analyze the material and structural behavior at failure using the ABAQUS™ non-linear solver. The failure load from the compression test was applied to an FEM of each panel to study the material behavior when failure occurred. At the conclusion of the simulation, the reaction loads in the skin near the skin/rib interface were compiled and applied to a two-dimensional refined joint model that determined the value of J1 present at that location on the panel. The first strain invariant in the test panel at failure was compared with the allowable J1 value; this process is demonstrated in Figure 7. Figure 8 displays the J1 response of the Baseline panel. The panel's first strain invariant exceeded the critical value, 2.51 E-3, in the locations that the test panel experienced delamination, indicating that joint peel-off was the failure mode.

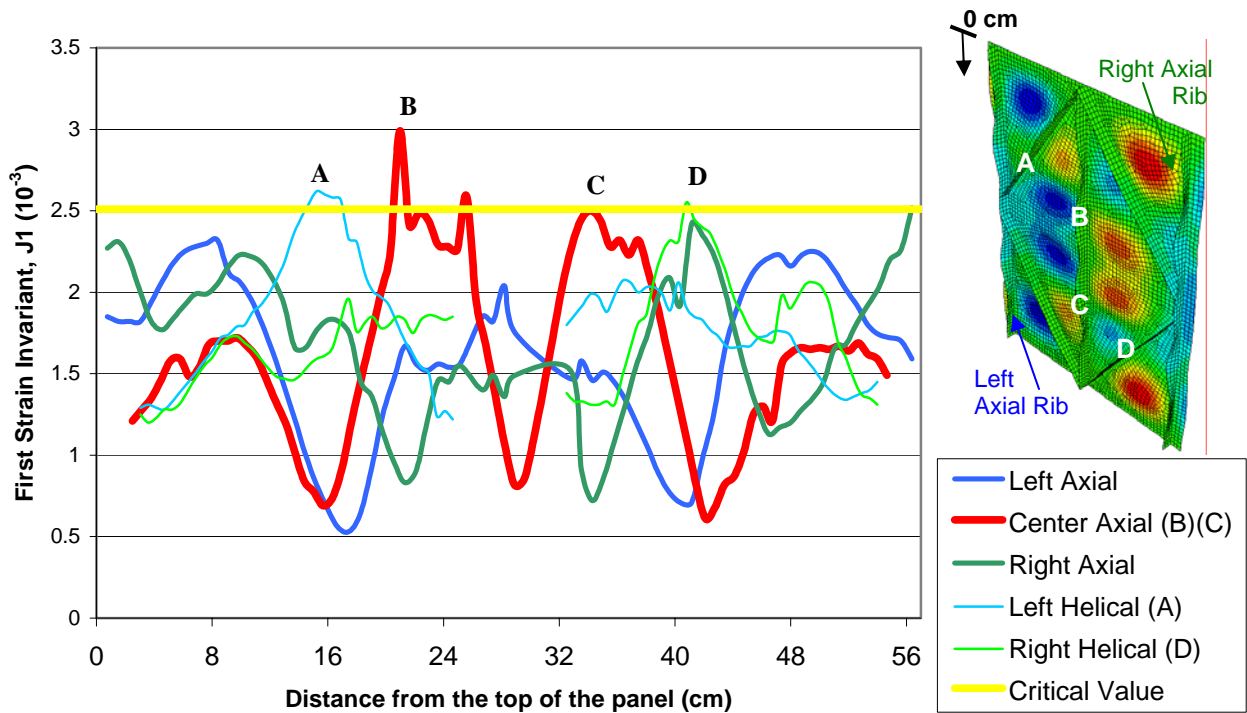


Figure 8. Baseline Panel J1 Response

The results obtained from the opposing strain gages on the empirical test panel indicated that the middle vertical rib did not buckle during the compressive test; likewise, the simulations indicated that the overall response of the reinforced panel was improved. Figure 9 displays a contour plot of the displacement in the 3-direction superimposed on the panel's deformed shape. The foam inserts are hidden in the Rohacell Reinforced plot so the skin behavior is visible. The Baseline panel exhibited local skin and rib buckling, whereas the Rohacell Reinforced panel did not experience any visible local buckling. Instead, it buckled globally about a hinge in the center of the panel. Additionally, the maximum displacement of the reinforced panel was 0.16 cm, less than the 0.19 cm in the Baseline model, lending further credence to the claim that the foam significantly supported the grid structure.

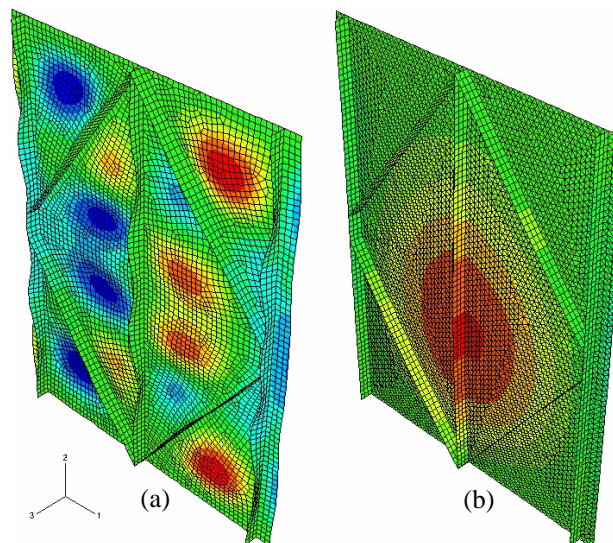


Figure 9. Deformed Shape of the (a) Baseline and (b) Rohacell Reinforced Panels

The same peel-off strain analysis was conducted for the reinforced panel as the Baseline. Since the Baseline analysis found the peak J1 values in locations similar to where the Baseline test panel delaminated, only the delaminated regions were inspected for the foam reinforced model. The study found that the highest strain invariant present in the Rohacell Reinforced panel was less than one percent of the allowable value. The foam increased the strength of the panel and prevented joint peel-off failure. After the J1 analysis, three additional failure modes were examined: joint pull-off, joint shear, and structural buckling.

Joint pull-off is a grid-stiffened structure failure mode common in designs with thick skin that have a high bending stiffness. The Rohacell Reinforced panel did not have a thick skin, but the combined effect of the eight ply skin and the Rohacell foam created a stiff skin. Pull-off failure occurs when the tensile strength of the adhesive layer between the skin and rib structures is exceeded. The section forces from the rib elements were collected to determine the normal stresses pulling the rib off the skin. Figure 10 displays the results of the inspection. The maximum stress occurred at the base of the panel, but was only 40 percent of the allowable value.

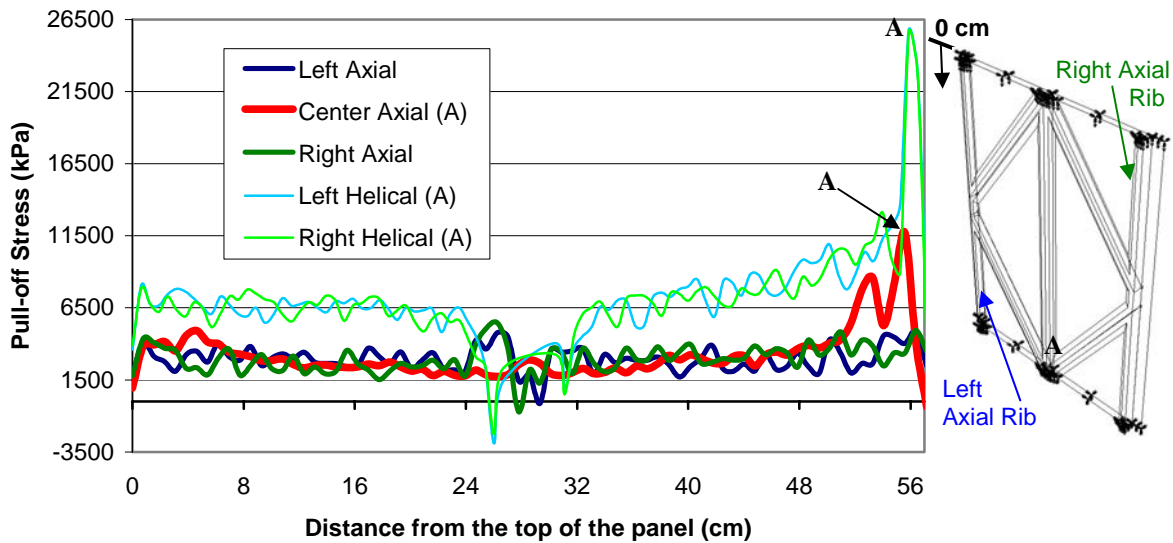


Figure 10. Rohacell Reinforced Panel Joint Pull-off Stresses

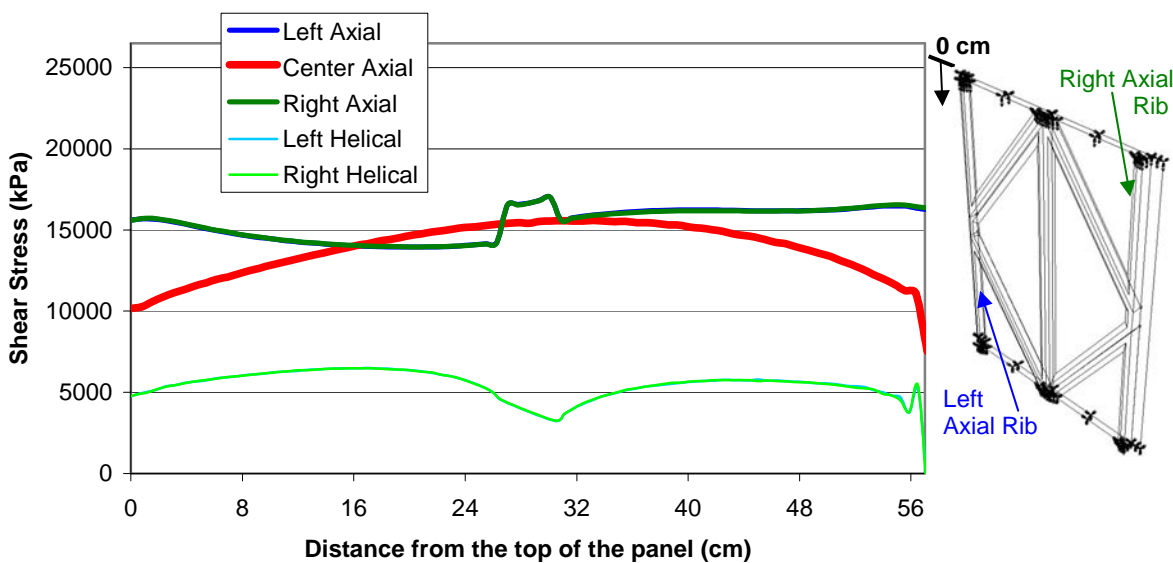


Figure 11. Rohacell Reinforced Panel Joint Shear Stresses

The final AGS specific failure mode explored was joint shear failure. Joint shear failure occurs when the shear capability of the adhesive is exceeded as the shear force is passed from the rib structure to the skin detail. The section force in the rib's 1-direction was divided by the area across the bottom of the rib's shell elements to calculate the shear stress being transferred from the AGS to the skin. The results are displayed in Figure 11. The panel's joint shear stress results are interesting because they were the most continuous response obtained. The allowable shear stress of the resin is estimated to be 62,000 kPa, which was not approached in the panel; thus joint shear was not the failure mode.

The panel models were then modified to conduct a buckling analysis by applying rotational constraints which forced the stiffeners to buckle in the plane perpendicular to the skin's original plane. Each model was compressed by means of a constant displacement until the structure buckled globally. The final compressive load was regarded as the structure's maximum load carrying limit. The non-reinforced Baseline panel achieved only a small fraction of its buckling limit; whereas the Rohacell Reinforced panel realized 85 percent of its theoretical buckling load. The conclusion of this analysis is that structural buckling was the controlling factor in the foam-reinforced concept.

III. Program Status

An effort was made to increase the number of Baseline and the Rohacell Reinforced test panels; however, a repeatable process for bonding the structural foam to the panel was not in place. Currently, a reliable fabrication process for the foam reinforced panels is being investigated. Fabrication and testing of additional test panels will follow to improve the test data confidence level. Large curved test panels are also being produced to increase the fidelity between the test articles and an axi-symmetric launch vehicle. The panels are expected to be tested in the spring of 2005.

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